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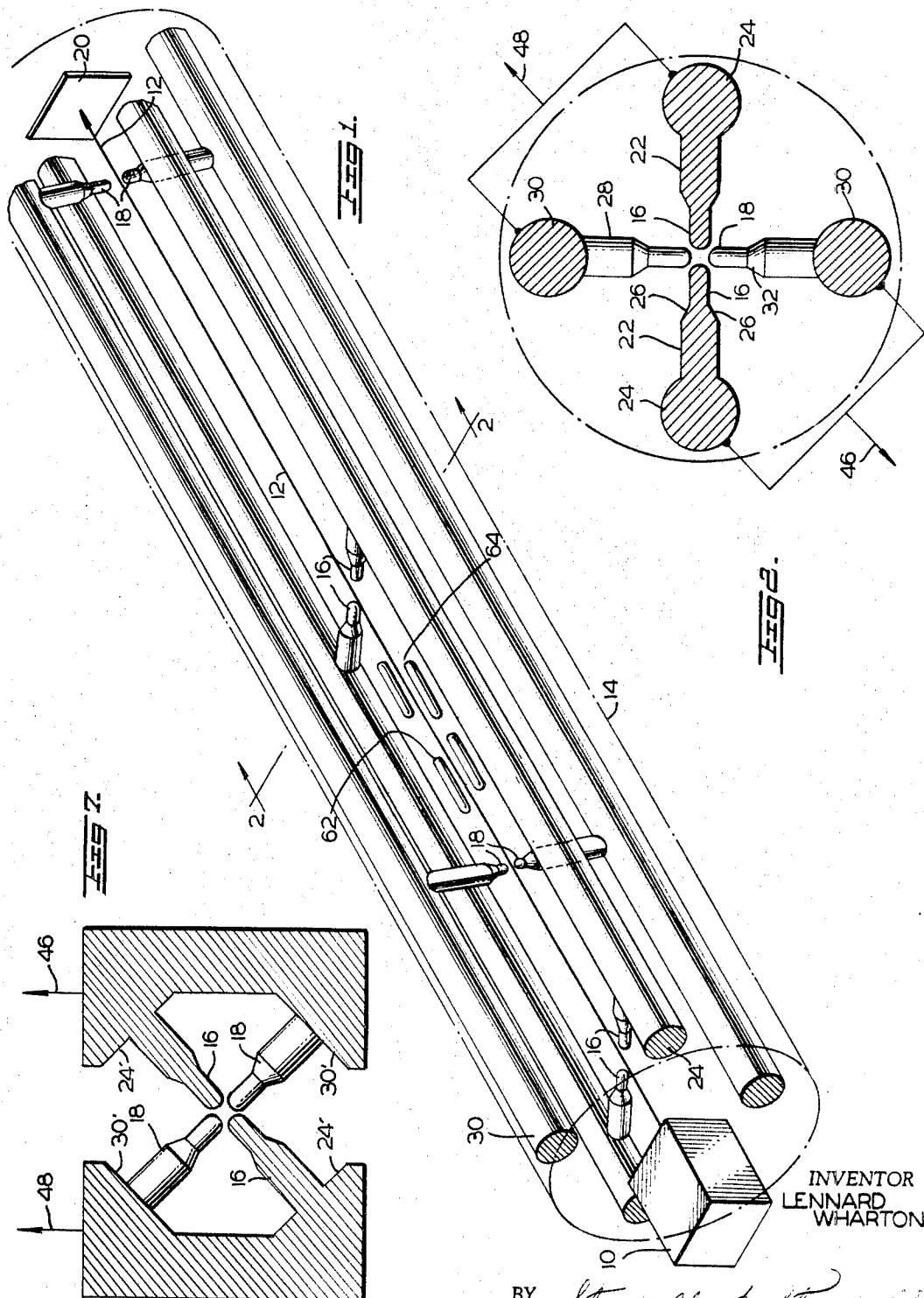
L. WHARTON

3,402,358

NEUTRAL PARTICLE BEAM ACCELERATOR HAVING TRANSVERSE ELECTRODES
AND STEERING MEANS FOR THE PARTICLE BEAM

Filed Nov. 9, 1964

2 Sheets-Sheet 1



INVENTOR
LENNARD
WHARTON

BY *Stowell & Stowell*
ATTORNEY

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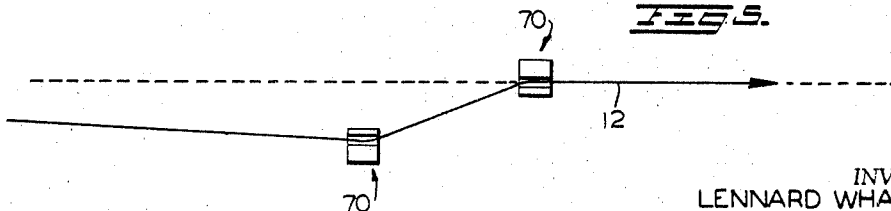
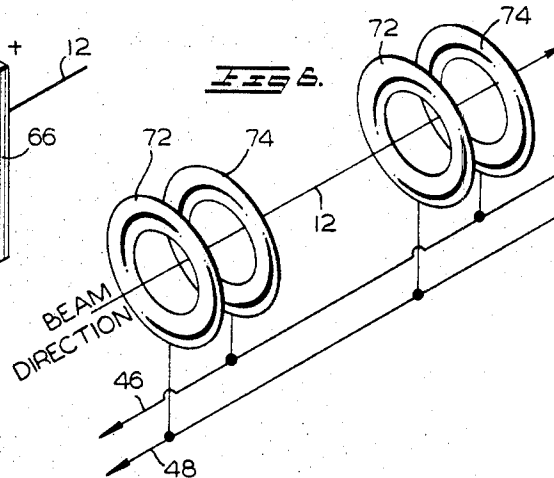
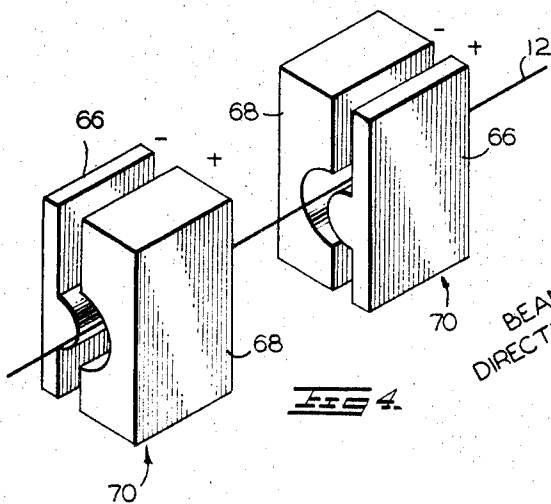
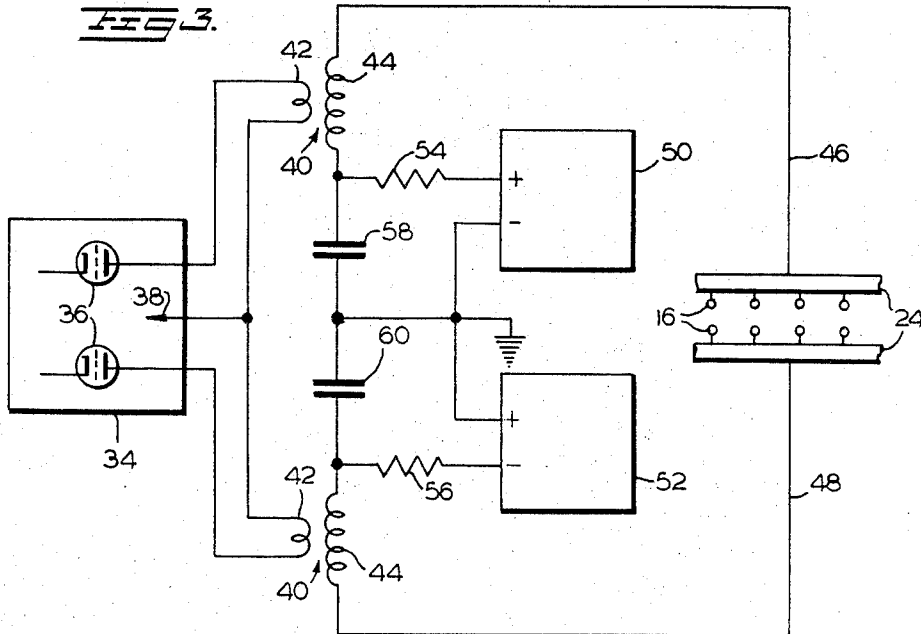
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INVENTOR
LENNARD WHARTON

BY *Stoull & Stoull*
ATTORNEY

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NEUTRAL PARTICLE BEAM ACCELERATOR HAVING TRANSVERSE ELECTRODES AND STEERING MEANS FOR THE PARTICLE BEAM

Lennard Wharton, Chicago, Ill., assignor to Research Corporation, New York, N.Y., a non-profit corporation of New York

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14 Claims. (Cl. 328—233)

ABSTRACT OF THE DISCLOSURE

A neutral particle accelerator is defined by a source of neutral particles and axially spaced electrode pairs whose electric fields polarize neutral particles. Successive electrode pairs are angularly spaced ninety degrees from each other for a beam focusing effect. Dipolar doublets, spaced along the particle beam path, also focus the particle beam. The spaced electrode pairs are operated at the same electrical phase.

The present invention relates to a particle accelerator, and more specifically to an apparatus and method for accelerating electrically neutral particles.

It is an object of the present invention to accelerate or decelerate efficiency to a predetermined velocity a molecular or atomic beam composed of neutral particles by means of a linear array of electric fields modulated at radio frequencies. As used in the preceding statement, the term efficiently means the efficient utilization of the available flux of particles injected into the accelerator so as to produce an intense beam. The term efficiently does not refer to the conversion of electrical energy into molecular energy, since owing to the losses involved, efficiency in such conversion is not readily possible.

A further object of the present invention is to produce a molecular beam accelerator comprising a series of individually designed accelerating stages collectively arranged in a linear array, together with auxiliary steering means and focusing means as required to achieve efficient particle acceleration.

A more specific object of the present invention is to provide a molecular beam accelerator comprising, in combination, a source of beam particles to be accelerated, the molecules or atoms of which are electrically neutral; means to accelerate such particles by forces arising from successive and periodically applied electric fields acting externally to the particles which electrically polarize the molecules or atoms; means to confine the polarized molecules into an intense beam; and target means to effectively utilize the accelerated beam.

Throughout the specification and claims the words "atom," "molecule" and "particle" may be used interchangeably within the concepts of the invention. However, it will be realized that the acceleration of polar molecules is more practical, due to the large interaction of such a particle with an externally applied electric field.

The molecular beam accelerator of the present invention has utility in the exploration of the theories of molecular cross-sections for inelastic collision processes, and to

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provide experimental data as a means to understand more profoundly the nature of gas-phase chemical reactions, as well as gas-liquid and gas-solid accommodation processes. In addition it may be useful as a means to promote specific or general, physical or chemical changes. Such an accelerator produces a beam of molecules traveling with a uniform and high kinetic energy, and could provide much information on the conversion of translational energy to rotational energy or vibrational energy from the lower states through the continuum. A molecular accelerator could be a fundamental tool for these types of investigations. The molecular beam accelerator has properties inherent in its design which are of particular value in studying molecular collisions, since the device produces an intense, focused beam, which is nearly monoenergetic.

A molecular accelerator opens up a number of additional possibilities for experimentations beyond the areas of chemical physics. The same device, for example, may be used to decelerate molecules or atoms in a molecular beam for the purpose of increasing the accuracy of an atomic clock. At its high energy ranges of operation it has utilization as a device for the study of the behavior of air foils at hypersonic velocities. With the efficiency of energy conversion improved by several orders of magnitude, such an accelerator could be used as the basis of an extraterrestrial rocket engine.

A still further object is the use of the molecular beam emerging from the accelerator to promote specific practical physical or chemical changes in or on a target. Three properties of the beam make this object of particular significance. First is the high intensity of the emergent beam. Second is the uniformity of the emergent beam energy. It is possible that very specific changes may be effected in or on the target through the accurate control of the beam energy available from the accelerator. Third is the high energy of the particles made available by the accelerator. This may make possible changes in or on the target, which may comprise other beam particles or a solid substance, for example, of a nature difficult or impossible to obtain by other means. These properties in combination would also be of utility in effecting practical changes.

With the above objects and uses of the molecular beam accelerator in mind, a preliminary discussion of its operation in terms of both the acceleration requirements and the aforementioned efficiency follows. This efficiency is achieved through a combination of means which include exploiting phase stability; providing beam focusing; working with as high electric fields for accelerating and focusing as possible; preventing nonadiabatic transition; and providing steering fields to direct the beam correctly through the apparatus.

As beam particles in dielectric states enter the gap between a pair of accelerating electrodes they will gain kinetic energy, but in traveling into and then out of the gap, the particle will not experience any net gain in kinetic energy if the electrode voltage is maintained constant, since the gain in energy in entering the gap is exactly cancelled by the loss of energy in leaving the gap.

Any change in kinetic energy is the negative of the change in potential energy. In the discussion of the energy of molecules or atoms in applied electric fields, it is usual to speak in terms of the change in potential

energy with applied field. Thus, for example, a molecule in a dielectric state loses potential energy in the electric field. Such a particle would be attracted to a region of strong electric field and gain kinetic energy; the gain in kinetic energy is exactly equal to the loss of potential energy, and is thus positive.

Since there are always a variety of distinct molecular or atomic states it is often possible to have some states present in a molecular or atomic beam that are dielectric and some that are "paraelectric," i.e., some states that will gain kinetic energy in passing into an electric field and some that will lose kinetic energy in passing into an electric field. The sign of the change in energy will very often depend upon the strength of the applied field. In general, in the limit of infinite electric field, all states become dielectric in behavior and all tend to the same value of dielectric polarizability. In the design of an accelerator for particles that behave in a specific manner in an electric field, it is important that all the states to be accelerated have the same or nearly the same energy change in an applied electric field. This is accomplished for some classes of particles by working at as high electric fields as is possible. Furthermore, since it may be inevitable that some of the states possible will not have a behavior sufficiently similar to that required for acceleration, it is necessary that one prevent transitions of molecules from states that are favorable for acceleration to those that are unfavorable for acceleration during the acceleration process. This type of transition can occur when non-adiabatic transitions are not suppressed in the fields of the accelerator. It is therefore important to suppress these non-adiabatic transitions.

For the purpose of the detailed description of a possible realization of the invention which follows, one may consider only those molecules which have sufficient dielectric polarizability to be accelerated, and assume that for this class of molecular states the behavior in an electric field is identical. It can be shown that for the considerations of phase stability and focusing this is a good assumption. Some or all of the molecules in states that do not fall in this category will travel in unstable orbits and not reach the far end of the accelerator.

Further objects and advantages of the invention, as well as certain theory necessary to its operation, will become apparent in the following description and claims, taken together with the accompanying drawings, wherein:

FIG. 1 is a perspective view of a linear molecular beam accelerator;

FIG. 2 is a transverse section taken along the line 2—2 of FIG. 1, to an enlarged scale, showing details of the accelerator electrode structure;

FIG. 3 is a schematic diagram of a high frequency source for energizing the electrode assemblies;

FIG. 4 is a perspective view, to an enlarged scale, of beam steering pole pieces suitable for use with the accelerator of FIG. 1;

FIG. 5 is a plan view of a beam path when the steering field devices of FIG. 4 are utilized;

FIG. 6 is a transverse section showing a modification of the accelerator structure; and

FIG. 7 is a perspective view of an alternative construction for the linear beam accelerator shown in FIGS. 1 and 2.

In FIG. 1 reference numeral 10 indicates any suitable molecular beam source from which particles effuse in a beam path 12 directed along the central axis of an evacuated chamber or tank 14, here represented in phantom outline. The beam of particles, after acceleration through the electrode assemblies 16, 18 is directed against a target holder 20. Such target holder is suitably mounted transverse to the tank axis and to the path of the beam. It has been shown located within the evacuated chamber so that it may be evacuated by the same pumps, not shown, which pump out the tank 14. Alternatively this

same target holder 20, or a secondary target supported in alignment therewith, may be disposed exteriorly of the tank 14 to facilitate its removal or replacement without destruction of the vacuum established within the accelerating chamber. The target may be a liquid, gas, solid, or colloid suitably placed with respect to the beam emerging from the accelerator. If it consists of a condensed phase, it may be held by the holder as described above. If it consists of a gas, the gas may be retained in a scattering chamber, or may emerge from any suitable source such as a hypersonic nozzle, molecular beam, or accelerator.

Beam source 10 is supported exteriorly of the tank with its effusion window or hole in coaxial alignment with the tank and the electrode assemblies. Source 10 is a conventional molecular beam source such as a Knudsen effusion cell which produces beams which are in thermal and chemical equilibrium or, for example, a hypersonic nozzle source.

Two features are essential for acceleration; electrode pairs or groups that produce a localized region of a strong electric field along the path of motion of the beam particles when connected to a voltage source; and a radio frequency oscillator to rapidly raise and lower the applied voltage to such electrodes. 16 represents a pair of hemispherically ended metal rods located on opposite sides of the beam of particles. They are spaced apart a distance which is large enough to minimize the possibility of sparkover, yet are maintained reasonably close to one another in order to produce as large an electric field as possible in a small volume for the purposes of acceleration and focusing.

Rods 16 are supported transversely of the beam path by segments 22 of a larger diameter rod. Such rod segments may be a prolongation of the hemispherically shaped rod ends 16 as indicated in FIG. 2, or they may be formed of a different conductive material. They are of larger diameter so as to provide greater rigidity and to conduct the radio frequency current to the electrode ends. The base portions of the rod segments 22 are secured electrically and mechanically, for example, by welding, to the distribution bus bars 24 to which the radio frequency voltage is applied.

The rod segments 22 and the hemispherically shaped electrodes 16 can be formed of different metals, particularly in the case where the electrodes themselves are formed of different materials to advantageously serve as an anode and a cathode with respect to the polarity of the applied voltage. Further, it will be noted that the junction between the members 16 and 22 is smoothly faired at the portion 26 so as to reduce any tendency for electrical sparkover. An insulating cover, not shown, may be provided over the bus bars 24 and the rod segments 22, and it may extend out to the electrode rods 16.

Spaced beyond the paired electrode assembly 16 in the direction of motion of the particle beam along its path 12 are a second pair of hemispherically ended metal rods 18. This additional accelerating electrode assembly is displaced ninety degrees, mechanically, from the preceding pair 16, but in all other respects is a duplicate of the previously described accelerating gap arrangement. That is, rods 18 are supported in a spaced relation on opposite sides of the beam path 12 by means of rod segments 28 which secure them electrically and mechanically to the distribution bus bars 30; are provided with a faired portion 32; and may be formed of different metals, with an optional insulating cover over certain areas.

This arrangement of spaced accelerator electrode assemblies or pairs 16 and 18 is repeated successively in a direction along the beam path 12, and the spacing between successive pairs increases along this path. Only a limited number of electrode assemblies have been illustrated in FIG. 1, for the purpose of clarity.

A maximum amount of acceleration is achieved by having the maximum voltage applied to the electrodes while the particle enters the field, and shutting off the voltage as the particle leaves the field. In this manner the maximum gain of kinetic energy is achieved for the particular peak voltage applied. Application of the accelerating voltage as a switched on-and-off square wave ideally produces the maximum acceleration, and if the applied voltage is modulated sinusoidally the gain in kinetic energy is only about 75% of that obtained for a square wave of the same peak voltage. However, since it is more convenient to utilize sinusoidal voltages, for reasons of power utilization efficiency and phase stabilization, sinusoidal voltages are provided by means of a radio frequency source which is shown in detail in FIG. 3.

Particles which are out of phase with the applied sinusoidal voltage receive less than the maximum gain in kinetic energy, and this is measurable in terms of the phase angle ϕ , where ϕ is the phase of the radio frequency sinusoidal voltage at the time when the particle is in the center of an electrode gap. This phase angle is defined as zero for the case of maximum acceleration. It is the particular periodic behavior, varying roughly as the cosine of ϕ , of the gain in kinetic energy vs. the phase angle ϕ that makes possible the efficient cascading of a series of individual accelerating stages, as discussed below.

In addition to the accelerating effects of a single stage, one must also consider the effects of each accelerating stage upon motion perpendicular to the direction of the molecular beam along the path 12; that is, the focal properties of the successive accelerating stages. For the case of the electrode configuration shown in FIG. 1, the beam is subjected to diverging forces in the plane containing the axis of the electrode rods and the molecular beam axis, and is subjected to converging forces in the plane perpendicular to the rod axis. Thus the accelerating stage acts as a converging lens for motion perpendicular to the electrode axis, and as a diverging lens for motion in the direction of the electrode axis and perpendicular to the beam axis. A series of stages with these focal properties can be arranged to give a net convergent effect through the exploitation of the principle of dynamic stability or, as it is called in charged particle accelerators, alternate gradient or "strong" focusing.

One desires to cascade the energy gain of a single stage through the construction of an accelerator that subjects the particle to a series of accelerations. This is accomplished through the construction of an array of these accelerating stages in series, most typically along a straight line, in such a way as to exploit the advantages of phase stability. It is known that a serial array of accelerating stages that have the accelerating properties described above may be cascaded, as the principles to be followed have already been elucidated in the case of charged particle linear accelerators. Since it has been stated above that the energy gain is a simple periodic function of the radio frequency phase angle, it does not matter whether this energy gain is as the result of the energy of interaction of an electrically neutral molecule with an electric field or a charged particle with an electric potential. Once the energy gain has been computed for the electrode system and the voltage of operation and electrical properties of the particle, the particle can be treated as if it had a net electrical charge equal to the ratio of the maximum energy gain per stage to the peak applied voltage.

The synchronous particles will cross the gap at radio frequency phase angles ϕ of between $-\pi/2$ and 0, in the region where there is an increase of energy with phase angle. Therefore, the spacing between successive stages will be made such that for the synchronous particles the phase angle is the same, modulo 2π , at every stage. The spacing will be in the simplest case increased as the square root of the particle's energy directly as the particle velocity

increases along the accelerator path, although certain engineering modifications and refinements may provide a more sophisticated and varied solution to insure that the phase angle of the synchronous particle is kept at the same modulo 2π .

The advantage to be gained through this exploitation of phase stability is enhanced efficiency of utilization of the injected beam and hence a greater accelerated beam intensity. This increased utilization means that particles that are considerably out of phase with respect to the synchronous particle and particles that have kinetic translational energies considerably different from the synchronous particle can be successfully accelerated. The larger the maximum energy gain possible per stage, the larger is the energy bandwidth and duty cycle over which successful acceleration can be effected for a device with a fixed number of stages and fixed overall energy gain. This is another reason why the electric fields in the accelerating stages should be as large as possible.

The energy band originally admitted from beam source 10 to the accelerator is, to a zeroth order of approximation, unchanged as a result of the acceleration process, although one can reduce the energy spread by debunching in the last few stages, such that the energy bandwidth can be reduced by a factor that is the order of magnitude of the fractional duty cycle of the accelerator. Debunching may be accomplished by one or a series of stages almost identical with the accelerating stages 16, 18; but with their spacing changed, so that for the synchronous particle the energy gain is zero and the phase angle is $-\pi/2$.

For the greatest intensity of the accelerated beam consistent with good design, the energy bandwidth accepted from the injected beam source 10 by the accelerator should about equal the range of translational energies present in the injected beam. This energy bandwidth accepted by the accelerator is variable with the voltage applied to the accelerating electrodes. Hence, it is a property of the device that the range of energies of the accepted entering particle, and therefore the particle emerging from the accelerator, may be controlled by the applied radio frequency voltage; the lower the voltage, the narrower is the emergent energy range. There is a sacrifice in intensity when the emergent energy range is narrowed in this manner.

The size of the accelerating electrode pairs, their successive spacing along the beam path 12, together with the particle mass and velocity of movement determine the frequency of operation of the radio frequency source. One such suitable source is shown in FIG. 3, which operates at a frequency of 0.4 to 0.5 megacycle.

Block element 34 represents the final output stage of a radio frequency oscillator. This may be a conventional transmitter oscillator having a power rating of fifteen to fifty kilowatts. Only the plate circuit of the power output tubes 36 is shown. High voltage is applied to the tube plates from a supply source within the oscillator, not shown, at the connection point 38.

Radio frequency step-up transformers 40 are provided for the purpose of raising the voltage potential applied to the accelerating electrodes via the conductive bus bars. Bars 24 which supply the electrodes 16 are visible in FIG. 3, and bars 30 which supply the electrodes 18 will be understood to lie in a plane which is normal to that of the drawing sheet. The transformer primary windings 42 are connected in the plate load circuit of the oscillator tubes 36, while one end of each of the secondary windings 44, jointly connected so that the voltages appearing in leads 46 and 48 is the sum voltage, is connected to one each of the bus bars 24 and 30 by the separate leads 46 and 48 in the manner indicated in FIG. 2.

The opposite ends of the secondary windings 44 are returned to direct current bias levels provided by the

power supplies 50 and 52. These may be high voltage supplies of the same or different voltages and of the polarities as indicated in FIG. 4 as required to initially bias the accelerator electrodes, but of a magnitude exceeding the peak radio frequency voltage to avoid a change in polarity of leads 46 and 48, and further to insure that there is a minimum voltage on the electrodes at all instants of time.

Current limiting resistors 54 and 56 are included in the connections to the transformer secondary windings from the bias supplies 50 and 52, and bias capacitors 58 and 60 are returned to ground potential to complete the oscillator load circuit.

The inductive reactance of transformers 40; together with the effective reactance of the electrode assemblies 16 and 18 and their supporting bus bars, which is principally capacitive; the reactance of the bias capacitors and the connective wiring, is adjusted so that a tuned load circuit is formed which is in resonance with the excitation frequency supplied by tubes 36.

The circuit shown in FIG. 3 may also be provided with variable capacitors, inductors, or taps on the step-up transformers to vary the resonant frequency of the accelerator circuit to provide changes in the frequency of operation and hence in the velocity of the emergent particles. The resonant circuit should have as low a dissipation factor as possible so as to reduce the losses arising from the circulating currents.

The effects of several accelerating stages upon dielectric particle motion as described above can have a net focusing effect when alternating gradient focusing is utilized. To explain such focusing effect further, since it can be

shown that the divergence of the forces $\Delta \vec{F}$ acting upon these particles is positive or zero, it is impossible to use static means to focus them, and one must use the techniques of dynamic stability. In the construction as described in which each accelerating stage consists of a pair of opposed hemispherical rods, the paraxial rays are subjected to a linear diverging force $F_x = +k_x X$ where x is a measure of the distance from the beam axis in the direction of the rods' axis. The paraxial rays are also subjected to a linear converging force in the direction perpendicular to the beam axis and perpendicular to the rods' axis $F_y = -k_y Y$. The force constants k_x and k_y , which are positive, are functions of the positions of the particles along the beam axis and of the applied voltage; but $k_x \leq 2k_y$. This would imply in the static case that the particle orbits would be unstable with respect to divergence. By spacing successive stages properly, and alternating their orientation along the beam axis so that the rod axes are perpendicular to each other in successive stages, as shown in FIG. 1, one can achieve a condition of alternate gradient or so-called AG focusing in which the beam is widened in the converging planes so that it is subjected to larger converging forces, while also it is narrowed in the diverging planes so that it is subjected to smaller diverging forces. Equations of motion have been developed and solved for this situation. The solutions of these equations, which are best exemplified by Hill's equation, have both regions of bound periodic solutions and unbound divergent solutions. The proper design seeks naturally those external parameters that give rise to bound motion in the coordinates perpendicular to the beam axis. Since these parameters must also satisfy the requirements of phase stable acceleration as well, it could well be that in certain situations there would be need or desirability for additional focusing electrodes which are independent of the accelerating electrodes. This additional focusing can be provided by such an arrangement as, for example, a dipolar doublet illustrated by the elements 62 and 64 in FIG. 1. One pair of dipole elements 62 is mounted spanning the beam path 12 and lies in the plane of bus bars 24, while the other pair 64 is similarly mounted to lie in the plane of bus bars 30. Each dipole pair is energized

by a direct current potential with no power consumption. The known use of alternate gradient focusing in the charged particle accelerator field indicates the practicality of this additional focusing system where required or desirable.

The focusing effects due to the accelerating electrode assemblies may in some practical cases be effectively net divergent, while those properties of the dipolar doublet described above may be used to converge the beam in practice. Proper use of one or many dipolar doublets could prevent loss of molecules in the accelerating process, and make the emergent beam intensity independent of the number of accelerating stages. Moreover, this would insure that the optics of the accelerator have a large aperture, with consequent enhancement of intensity. Conversely the coupling between the accelerative and focal properties provides a natural means of partially or completely eliminating molecules in states unfavorable for acceleration: some or all molecules in this class will follow unstable orbits and be thrown out of the beam. This will insure that the beam will consist more nearly or entirely of molecules that were suitably accelerated, and thus insure a more narrow velocity distribution in the emergent beam.

In one practical design example for a molecular beam accelerator in accordance with the invention, as illustrated in FIGS. 1-3, the following arrangement of elements was used. The accelerator electrode assemblies consist of type 304 stainless steel rods of 0.25 millimeter radius, the gap ends of which are to be contoured to a hemispherical shape; carefully polished with 0.05 micron alumina abrasive. The spacing of the gap between electrodes 16-16, and also 18-18, is to be 0.5 millimeter.

The vacuum tank 14 is to be constructed so as to isolate the accelerator section from the beam injector and target chambers, and is to be approximately one-half meter in diameter, and from seven and one-half to ten meters long. A suitable material for tank 14 is stainless steel with evacuation by means of ion pumps or mercury or oil diffusion pumps to a pressure of less than $(10)^{-7}$ torr.

The vacuum system to be utilized must satisfy the requirements of (1) prevention of scattering of the beam by residual gas in the accelerator so that such beam is neither attenuated, slowed down, altered in state, or defocused; (2) prevention of electrical breakdown as a result of residual gas or contamination; and (3) the aforementioned isolation of the accelerator section from the injector and target chambers so that possible higher pressures present in these adjoining sections will not affect operation of the accelerator.

Because of the high-voltage requirements, organic contamination of the system may in practice need to be kept to a minimum, and hence the use of mercury diffusion pumps and metallic gasketing is indicated, and since certain scattering experiments may require the use of noble gases, ion pumps that do not pump these gases well enough cannot be used. One or more high-speed mercury diffusion pumps with refrigerated baffles and liquid nitrogen traps will be required so as to satisfy the first two requirements. The isolation requirement may be achieved through separate pumping systems or the use of differential pumping where necessary.

High voltages may be introduced into the vacuum system by means of ceramic insulated bushings. The supports for the accelerating electrodes may include ceramic insulator means that do not outgas.

A total of between seven hundred and one thousand successive accelerator electrode stages are to be enclosed within the vacuum tank, spaced apart in increasing distances along the beam path 12 with an overall average interstage distance of 1.4 centimeters.

There is no theoretical upper limit to the number of stages that can be cascaded efficiently in this manner. In the case where the electrode spacing becomes too large

for a high energy gain accelerator, harmonics of the first accelerating frequency may be used in second and higher sections of the accelerator. With this technique the electrode spacing is correspondingly reduced, and the energy gain can be made approximately linear with the length of the apparatus. In this manner one beam accelerator tank may be used as the injector for a considerably higher energy device of the same or different type.

A field strength across the accelerating electrode gap of substantially $1.0 \times (10)^6$ volts/centimeter is contemplated in this arrangement, using a peak voltage of sixty kilovolts across the 0.5 millimeter gaps.

With the biasing available in the circuitry of FIG. 3 this may be achieved with a rating of 17.5 kilovolts for each bias supply 50 and 52, and a peak radio frequency voltage from the step-up transformers 40 of 25 kilovolts.

The bias capacitors 58 and 60 are to have a capacity of .01 to .05 microfarad, which is substantially twenty to one-hundred times that of the electrode assembly so that the high voltages generated in the resonant circuit can appear across the electrodes. This will also insure that losses in the bias capacitors will have considerably smaller effects upon the dissipation factor of the circuit. The DC power supplies to maintain the bias voltage merely have to make up for the leakage currents across the bias capacitors and electrodes, which are estimated to be less than 1.0 microampere, hence the current loading of these power supplies will be very small.

In theory it would be possible to set the phase of succeeding electrode stages along the accelerator individually with phasing circuits, but it is simpler to operate all electrodes at the same electrical phase. Synchronization with the particles is most readily achieved through the proper spacing of the electrodes along the beam path. By this means one avoids the expense of phase shifting components and the difficulties in changing the frequency of operation.

The energy gain for the synchronous particle, which is the average energy gain per stage for all accelerated particles, is set in the design example at $E/k=33^\circ \text{C}$. Since a required energy gain of 2 ev. is equivalent to a temperature rise of $23,200^\circ \text{C}$., approximately 700 stages will be required. The energy bandwidth is to be of the order of 100°C .; the duty cycle 35%; and the range of rotational energies acceptable for acceleration about 40°C . The entrance aperture is calculated to be about $f:60$.

It may be necessary to provide steering fields to insure that small defects such as misalignment or misshape of the accelerating electrodes do not cause the accelerated beam to wander off the mechanical axis of the accelerator. To overcome such effects of electrode imbalance, pairs of steering fields may be used to change the path direction as shown in FIG. 5. A pair of suitable dipole field pole pieces 70 to be used for such a purpose is illustrated in FIG. 4. The design of such so-called "two wire" deflecting fields is known in the molecular beam art.

As shown in detail in FIG. 4, each pair 70 of the steering field pole pieces consists of one convex element 66 and a corresponding concave element 68 having a greater radius of curvature. Such pole pieces are located on either side of the molecular beam where required. They are energized by a direct current voltage, with polarities as indicated in FIG. 4.

A further use for deflecting or steering fields would be to provide a means for eliminating injected particles with too low an effective dipole moment to interact with fields in the accelerator. The origin of such particles could be molecules in high rotational states, polymers, or atoms. To eliminate these unwanted particles the mechanical axis of the electrodes of the accelerator could be deliberately bent or deflected in such a way that the beam particles would have to be successfully deflected by one or more steering fields in order to reach the end of the accelerator.

Non-adiabatic transitions are eliminated by insuring that the electric field experienced by the particles never

completely vanishes along the length of the accelerator. This is accomplished by the means which bias the radio frequency voltage as described above, and also by arranging the geometry of the electrodes, the bus bars, and their electrical connections in such a way that the beam particles are always immersed in an electric field. One possible means of producing such a field may be effected by shaping the bus bars 24 and 30, and/or the stub support means 22 and 28 such that these elements form a modified parallel-plate capacitor. Such alternative construction is illustrated in FIG. 7, where it will be apparent that the bus bars 24 and 30 of FIGS. 1 and 2 have been replaced by the opposed planar surfaces 24' and 30', respectively. Such conductive surfaces support spaced accelerator electrode assemblies 16-16 and 18-18, and are supplied with radio frequency energy by the separate leads 46 and 48 in the manner previously described in connection with FIGS. 2 and 3. The orientation of the electric field thus produced should be preserved in passing from one section of the accelerator to another, such as from an accelerating section to steering section; to a converging doublet section; etc.

The gas beam injector 10 is to be a conventional Knudsen cell to consist of a stainless steel tube filled with LiF, crimped at the ends, and heated by passing a large current through it, from which LiF effuses through a circular hole about 0.25 millimeter in diameter. The temperature is adjusted in the range of 1400°K . so that the vapor pressure of LiF gives rise to a mean free path for kinetic collisions inside the source that is the order of magnitude of the aperture diameter. This will give the maximum beam intensity for an effusion cell. Higher intensities may be achieved with hypersonic nozzle injectors. The final target or beam collector may be an emergent structure of conventional design.

Another important possible means of acceleration is through the use of axial fields, as contrasted with the transverse fields previously described. Also, the combination of these two possible means of particle acceleration is an obvious modification of the invention. An economical axial field design would limit the spatial extent of the field to minimize the stored energy. Only two stages of axial electrode pairs are shown in FIG. 6, but they are representative of a linear array of a number of such electrode pairs. These accelerating electrodes could be made conveniently in the form of toroids 72 and 74, that would be electrically connected to a radio frequency source such as that illustrated in FIG. 3 by the separate leads 46 and 48, respectively. One pair 72-74 would comprise an accelerating stage. The beam 12 to be accelerated would pass through the hole of the toroids; hence the internal diameter should be large enough to allow passage of the beam. As there are a large number of modifications of the exact shape and dimensions of the sort of electrodes that can produce an axial field that is suitable for acceleration, the above example is given for the purpose of illustration, rather than to restrict the exact specification of the electrodes that would be suitably constructed for producing an axial field.

Modifications of the design optics may be made. For example, it should be noted that FIG. 1 illustrates a pair of converging dipolar elements 62, 64 inserted along the molecular beam path 12 following two stages of accelerating electrodes. In actual practice the location and spacing of such convergent means may vary as required by the particular defocusing or divergent characteristics of the accelerating electrodes. In certain cases a single dipole element inserted along the beam path will produce the desired focus correction.

Modification of the illustrative example of design is possible, within the confines of the essential properties of the accelerator. In particular there are a variety of possible electrode shapes that will produce a relatively confined intense electric field when an outside source of voltage is applied. As this is the essential property of the ac-

celerating electrode pairs 16 and 18, variations of design that achieve this end within the realm of the known art of electrode design is an obvious modification of such accelerating electrodes. Similarly, modifications may be made as to the shape of the additional focusing elements such as the dipolar doublets 62 and 64. There are also a variety of fields that are known to deflect molecular beams that would be suitable as steering fields, and any of these are possible modifications of the steering field design represented by the steering field pole piece pair 70.

Further, the foregoing description deals with the example of the acceleration of dielectric particles, such as LiF which loses energy in the acceleration field. A modification to enable the acceleration of paraelectric particles such as NH₃ which has states that gain energy is described below. The general features of the beam source 10; accelerating electrodes 16 and 18; focusing means 62 and 64 where desirable; steering means 70 where desirable; and target holder 20 are preserved in scope, but modified to fit the needs of accelerating paraelectric particles.

Acceleration in the case of paraelectric particles with either axial, transverse, or combination fields is effected by voltages that are small when the particles enter the region between the accelerating electrodes and large when the particles are leaving this region. This is to be contrasted with the previously described condition for accelerating dielectric particles in which the voltages are arranged to be large when the particles enter the field and small when the particles leave the field. If in the case of paraelectric particles the radio frequency phase angle is defined to be zero for maximum acceleration, then cascading of successive stages to form a phase stabilized accelerator is identical to that for dielectric particles, and one follows the general principles discussed above as to the design criteria for cascading, voltage excitation, and electrode design.

Focal considerations for paraelectric particles are considerably simpler since the divergence of the forces will be negative. It may not be necessary to exploit the features of dynamic stability in this case, since static stability is possible. If opposed rod pairs 16 and 18 are used for accelerating stages, then an alternating gradient focusing system as previously described should be established. There is less likelihood for the necessity of additional focusing elements in this case because of the preponderance of converging tendencies. If axial accelerating fields as illustrated in FIG. 6 are utilized, it is possible because the field may be made a local minimum at the beam axis 12 that entirely static means of stability can be achieved, that is to say that each accelerating stage will be intrinsically convergent. Additional focusing means may be dipolar doublet pairs 62 and 64, as with the case with dielectric particles, but, in addition, quadrupoles, hexapoles, octapoles, etc., may be used in their place to converge beams of paraelectric particles.

In the case of paraelectric particles the optimal operating point may or may not be the maximum electric fields possible, depending upon the variation of energy with electric field.

I claim:

1. A neutral particle accelerator comprising, in combination, a source of neutral particles; means to accelerate a beam of said particles from said source to a target comprising a plurality of intervening accelerator electrode assemblies; means to converge the particles in said beam comprising at least one pair of spaced dipole assemblies whose field is transverse to said beam; a fixed high frequency source for energizing said electrode assemblies; and direct current sources for energizing said dipole assemblies.

2. A neutral particle accelerator comprising, in combination, a source of neutral particles; means to accelerate a beam of said particles from said source to a target comprising a plurality of intervening accelerator electrode assemblies; means to steer said beam including

at least two pairs of opposed pole pieces spaced apart in a direction along the path of said beam, the poles of each pair being located on opposite sides of said beam and transverse thereto; a high frequency source for energizing said electrode assemblies; and direct current sources for energizing said beam steering pole pieces.

3. A neutral particle accelerator comprising, in combination, a source of neutral particles; means to accelerate a beam of said particles from said source to a target comprising a plurality of intervening accelerator electrode assemblies; means to converge the particles in said beam comprising at least one pair of spaced dipole assemblies whose field is transverse to said beam; means to steer said beam including at least two pairs of opposed pole pieces spaced apart in a direction along the path of said beam, the poles of each pair being located on opposite sides of said beam and transverse thereto; a high frequency source for energizing said electrode assemblies; and direct current sources for energizing said dipole assemblies and said beam steering pole pieces.

4. A neutral particle accelerator comprising, in combination, a source of neutral particles; means to accelerate a beam of said particles from said source to a target comprising a plurality of intervening accelerator electrode assemblies; a high frequency source for energizing said electrode assemblies, said accelerator electrode assemblies comprising pairs of rounded electrodes spaced successively in a direction along the path of said beam, the electrodes of each pair being located on either side of said beam and transverse thereto.

5. A neutral particle accelerator comprising, in combination, a source of neutral particles; means to accelerate a beam of said particles from said source to a target comprising a plurality of intervening accelerator electrode assemblies, a high frequency source for energizing said electrode assemblies, said accelerator electrode assemblies comprising pairs of rounded electrodes spaced successively in a direction along the path of said beam, the electrodes of each pair being located on either side of said beam and transverse thereto; the axis of each successive electrode pair being angularly displaced from the axis of the preceding pair.

6. A neutral particle accelerator according to claim 4 wherein the spacing between successive pairs of said accelerator electrode assemblies is varied in a direction along the path of said beam in such a manner as to provide phase stable operation.

7. A neutral particle accelerator according to claim 1 wherein said dipole assemblies for converging the particles are located between certain of said successive accelerator electrode assemblies.

8. A neutral particle accelerator according to claim 1 wherein said one pair of dipole assemblies for converging the particles precedes the first accelerator electrode assembly.

9. A neutral particle accelerator according to claim 1 wherein said one pair of dipole assemblies converging the particles follows the final accelerator electrode assembly.

10. A neutral particle accelerator according to claim 3 wherein said dipole assemblies for converging the particles include two pairs of opposed dipoles spaced apart in a direction along the path of said beam; the plane of one pair being angularly displaced from that of its preceding pair.

11. A neutral particle accelerator comprising, in combination, a source of neutral particles; means to accelerate a beam of said particles from said source to a target comprising a plurality of intervening accelerator electrode assemblies; a high frequency source for energizing said electrode assemblies, said electrode assemblies producing a field which is transverse to said beam of particles.

12. A neutral particle accelerator according to claim 2 wherein said opposed beam steering pole pieces are sub-

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stantially cylindrical in form; one pole face being concave, and the other convex.

13. A neutral particle accelerator according to claim 12 wherein the said concave pole piece has a larger radius of curvature than said convex pole piece.

14. A neutral particle accelerator according to claim 13 wherein one pair of said beam steering pole pieces has a concave pole face located on one side of said beam, and the successive pair has a convex pole face located on the same side of said beam.

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14**References Cited****UNITED STATES PATENTS**

3,218,562	11/1965	Serduke	-----	328—233
3,067,359	12/1962	Pottier	-----	315—3 X
3,238,465	3/1966	Wuerker et al.	-----	315—3.5

DAVID J. GALVIN, *Primary Examiner*.

V. LAFRANCHI, *Assistant Examiner*.